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A study on the vibration of a bus with air suspension system moving on random road surface profiles with different speeds

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ABSTRACT

This paper presents the results of research on the vibration of the Hyundai Universe bus using an air suspension system and mechanical suspension system when it is run at different speeds on random road surface profiles according to ISO 8608:2016. The research results show that the used air suspension system ensures smooth movement and dynamic safety according to TCVN 6964:2008 (ISO 2631:2003) and VDI 2057:2017 standards. The maximum vehicle speeds on different road classes varied from 105km/h to 65km/h. A vehicle with an air suspension system provided a smaller root mean square of vibration acceleration RMS(Z) than a vehicle with a mechanical suspension system. The root means square of the wheel load RMS(Fz) of a vehicle with an air suspension system is about 99.6% of that of a vehicle with a mechanical suspension system.

1. Introduction

The vibration of the vehicle is evaluated according to two important criteria such as dynamic safety and smoothness of movement, specifically according to the available procedures and standards (TCVN 6964:2008; VDI 2057-1:2017). A number of researchers have studied and analyzed the vibration system of heavy vehicles like buses, agricultural machines and coaches. Among the related works, Hung et al. (2022), investigated and proposed the optimal air suspension system of buses using genetic algorithms. Long et al. (2018) studied the effect of bus suspension on the comfort of travel. The influence of stiffness and damping of suspension system components was also studied by Sekulic and Dedovic (2011). Rakheja et al. (1999) obtained the optimal suspension damping of an urban bus. In other similar work, Hostens et al. (2004) presented an improved design for air suspension of agricultural machines. Yang and Wang (2012) conducted a research on vibration response and signal processing of air suspension systems using wavelet transform method. Jiao and Nguyen (2021) analyzed the low frequency vibration of heavy truckers containing air suspension systems at different operational and working conditions. Nguyen et al. (2021a) compared the vibration response of mechanical suspension and air suspension systems. Nguyen et al. (2021b) also studied the effect of road surface irregularity on the vibration system of some kinds of buses. Li et al. (2011) worked on the fuzzy control of the air suspension system of a coach. Obst et al. (2020), investigated experimentally the characteristics of air springs of truck trailers. Siddiqui (2020) performed research to study the dynamic behavior of an urban bus on the quality of ride and wheel loads. Warczek et al. (2014), proposed a method for identification of damping coefficient for suspension system of trucks. Ha et al. (2022) determined the dynamic load reductions for a tractor vehicle equipped with air suspension at all axles. Jonsson et al. (2015) performed a study on the interaction of bus and seats by performing a vibration analysis. Sekulic (2020) investigated the roughness and waves of the road surface on the vibration response of bus vehicles. Ali and Frimpong (2018) also utilized artificial intelligence models for predicting the suspension system performance of large vehicles.

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Dynamic safety is used to evaluate drivability, the ability to transmit force between the tire and the road, and the durability of the vehicle and the road. Dynamic safety is evaluated by one of the following criteria: dynamic load factor (DLF), dynamic load stress coefficient (DLSC), load coefficient (LCmax, LCmin), maximum vertical force (F_{zmax}), and time the tire leaves the road surface (tl). The load coefficient is determined by the following formula (Jazar & Jazar, 2017; Tung et al., 2020):

$$LC = \frac{F_z}{F_{z,st}} = \frac{F_{z,st} + F_{z,dyn}}{F_{z,st}} \tag{1}$$

$$LC_{\min} = \frac{F_{z,st} + F_{z,dyn,\min}}{F_{z,st}}; \quad 0 \le LC_{\min} \le 1 \tag{2}$$

LC_{min} = 0.5 this is the warning limit (WL);
LC_{min} = 0 this is the intervention limit (IL).

$$LC_{\max} = \frac{F_{z,st} + F_{z,dyn,\max}}{F_{z,st}}; \quad 1 \le LC_{\max} \le 1.5 \tag{3}$$

LCmax ≤ 1.5 is the endurance limit of the vehicle and the road.

The smoothness of the vehicle's movement is dependent on the vehicle's structure, suspension, tires, road surface, and driving technique. The smoothness of the vehicle's movement is assessed by one of the criteria such as vibration frequency, vibration acceleration, root mean square of the vibration acceleration, and smoothness. The root mean square of the vibration acceleration is determined by the following formula (Jazar & Jazar, 2017; Tung et al., 2020):

$$RMS(\ddot{Z}) = \sqrt{\frac{1}{T}\int_0^T \ddot{Z}^2(t)\,dt}; \tag{4}$$

where: T is the vibration time; $RMS(\ddot{Z}) = 0.1\ m/s^2$ vibration has a pleasant feeling; $RMS(\ddot{Z}) = 0.315\, m/s^2$ vibration causes fatigue; $RMS(\ddot{Z}) = 0.63\ m/s^2$ vibration affects the health. The vibration acceleration of the bus in the three directions x, y, and z is limited as follows: $\ddot{x} < 1,0 m/s^2$, $\ddot{y} < 0,7 m/s^2$, $\ddot{z} < 2,5 m/s^2$.

2. The dynamics model

The Hyundai Universe bus has two axles using air suspension systems, and the dependent model. Fig. 1 shows the dynamic and vibrational model and elements used for the air suspension system of this vehicle. The method of structural division of the multi-body system is used in this paper to establish a dynamic model describing the bus vibration of the Hyundai Universe bus. The Newton-Euler equations are used to build the system of dynamic equations for this vehicle such as the system of Eq. (5) to Eq. (20) (Tung et al. 2021a,b; Tung & Huong 2021a,b, Thanh Tung 2021):

$$(m + m_{A1} + m_{A2})(\ddot{x} + \dot{\psi}\dot{y}) = F_{x1}cos\delta_1 + F_{x2}cos\delta_2 - F_{y1}\sin\delta_1 - F_{y2}\sin\delta_2 + F_{x3} + F_{x4} \tag{5}$$

$$(m + m_{A1} + m_{A2})(\ddot{y} + \dot{\psi}\dot{x}) = F_{x1}\sin\delta_1 + F_{x2}\sin\delta_2 + F_{y1}cos\delta_1 + F_{y2}cos\delta_2 + F_{y3} + F_{y4} \tag{6}$$

$$m(\ddot{z} - \dot{\varphi}\dot{x}) = F_{C1} + F_{K1} + F_{C2} + F_{K2} \tag{7}$$

$$J_x\ddot{\beta} = (F_{C2} + F_{K2} - F_{C1} - F_{K1})b_1 + (F_{C4} + F_{K4} - F_{C3} - F_{K3})b_2 \tag{8}$$

$$J_y\ddot{\varphi} = (F_{C1} + F_{K1} + F_{C2} + F_{K2})l_2 - (F_{C3} + F_{K3} + F_{C4} + F_{K4})l_3 \tag{9}$$

$$\begin{aligned} J_z\ddot{\psi} &= (F_{x1}\sin\delta_1 + F_{x2}\sin\delta_2 + F_{y1}cos\delta_1 + F_{y2}cos\delta_2)l_2 + (F_{x4} - F_{x3})a_2 \\ &+ (F_{x2}cos\delta_2 - F_{x1}cos\delta_1 + F_{y1}\sin\delta_1 - F_{y2}\sin\delta_2)a_1 - (F_{y3} + F_{y4})l_3 \end{aligned} \tag{10}$$

$$m_{A1}(\ddot{z}_{A1} + \dot{\beta}_{A1}\dot{y}_{A1}) = F_{CL1} + F_{CL2} - F_{C1} - F_{K1} - F_{C2} - F_{K2} + F_{B2} + F'_{B2} - F_{B1} - F'_{B1} \tag{11}$$

$$m_{A1}(\ddot{y}_{A1} - \dot{\beta}_{A1}\dot{z}_{A1}) = F_{y1} + F_{y2} \tag{12}$$

$$J_{Ax1}\ddot{\beta}_{A1} = (F_{C1} + F_{K1} - F_{C2} - F_{K2})\frac{b_1}{2} + (F_{CL2} - F_{CL1})\frac{a_1}{2} + (F_{B1} - F_{B2})\frac{c_1}{2} + (F'_{B1} - F'_{B2})\frac{d_1}{2} - F_{y1}(r_1 + \xi_{A1}) - F_{y2}(r_2 + \xi_{A2}) - M'_A \tag{13}$$

$$m_{A2}(\ddot{z}_{A2} + \dot{\beta}_{A2}\dot{y}_{A2}) = F_{CL3} + F_{CL4} - F_{C3} - F_{K3} - F_{C4} - F_{K4} + F_{B4} + F'_{B4} - F_{B3} - F'_{B3} \tag{14}$$

$$m_{A2}(\ddot{y}_{A2} - \dot{\beta}_{A2}\dot{z}_{A2}) = F_{y3} + F_{y3} \tag{15}$$

$$J_{Ax2}\ddot{\beta}_{A2} = (F_{C3} + F_{K3} - F_{C4} - F_{K4})\frac{b_2}{2} + (F_{CL4} - F_{CL3})\frac{a_2}{2} + (F_{B3} - F_{B4})\frac{c_2}{2} + (F'_{B3} - F'_{B4})\frac{d_2}{2} - F_{y3}(r_3 + \xi_{A3}) - F_{y4}(r_4 + \xi_{A4}) - M'_{A2} \tag{16}$$

$$J_{Ay1}\ddot{\varphi}_1 = M_{A1} - M_{B1} - F_{x1}r_{d1} \tag{17}$$

$$J_{Ay2}\ddot{\varphi}_2 = M_{A2} - M_{B2} - F_{x2}r_{d2} \tag{18}$$

$$J_{Ay3}\ddot{\varphi}_3 = M_{A3} - M_{B3} - F_{x3}r_{d3} \tag{19}$$

$$J_{Ay4}\ddot{\varphi}_4 = M_{A4} - M_{B4} - F_{x4}r_{d4} \tag{20}$$

In the next section the vehicle's vibration parameters (including accelerations, load coefficients and root mean square of vibration acceleration) are studied for the Hyundai Universe bus.

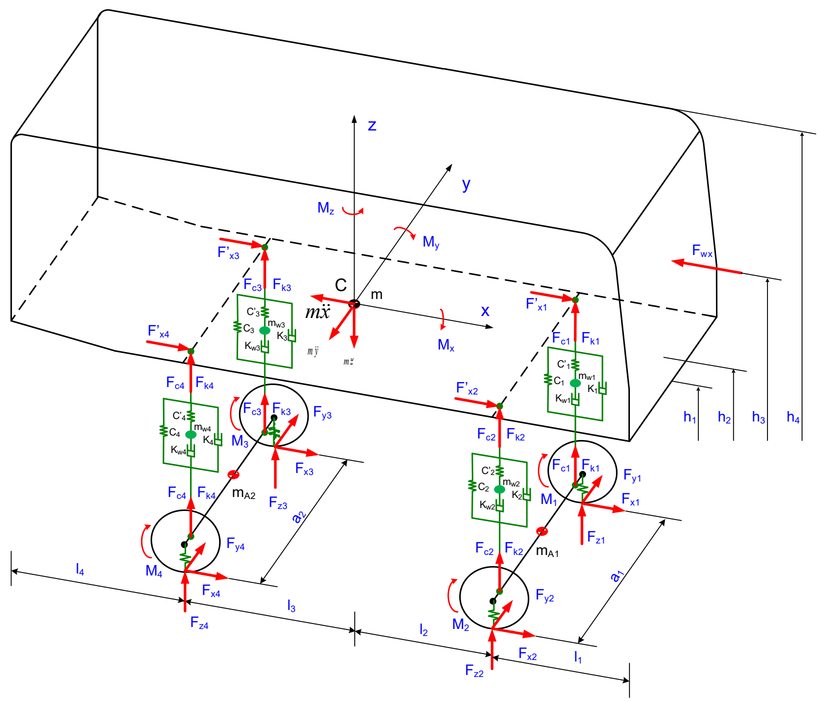
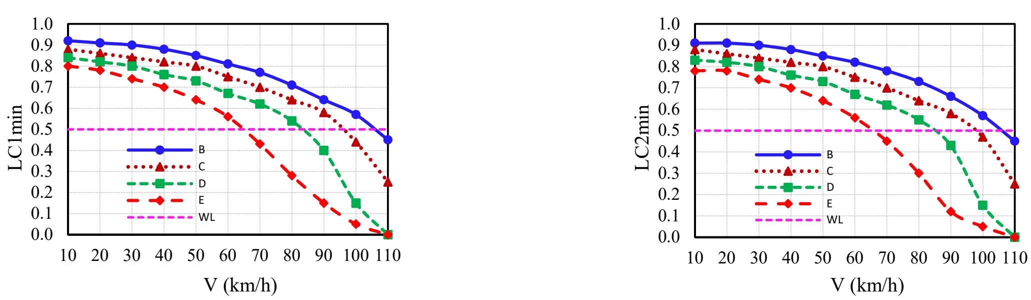


Fig. 1. The dynamics model of a bus using an air suspension system

3. Research results and discussion

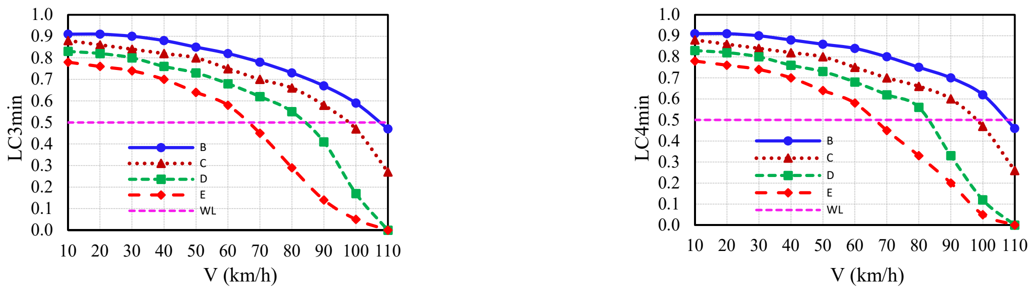
The Matlab software is applied here to survey some vibration evaluation parameters of the Hyundai bus such as vibration accelerations ($\ddot{x}_{max}$; $\ddot{y}_{max}$; $\ddot{z}_{max}$) ; load coefficients (LC_{max}, LC_{min}) and root mean square of vibration acceleration $RMS(\ddot{Z})$. The Hyundai Universe bus was surveyed at different speeds V=10 to 110 km/h with intervals of 10 km/h on random surface of pavement according to ISO 8608:2016. Fig. 2 shows the minimum load coefficient acting on the left and right front axle (LC_{1min}, LC_{2min}, respectively) when the vehicle is running at speeds between 10 and 110 km/h on the road surface. The WL line is the warning limit set at: (LC_{min}=0.5). As shown in Fig. 2, for a bus that is guaranteed to be dynamically safe, the speed must be less than 65 km/h when the vehicle is running on the "class E" road or less than 84 km/h when the vehicle is running on the "class D" road or less than 98 km/h when the vehicle is running on the "class C" road or less than 106 km/h when the vehicle is running on the "class B" road.



(a) (b)

Fig. 2. The minimum load coefficient determined (a) on the left and (b) the right front axle.

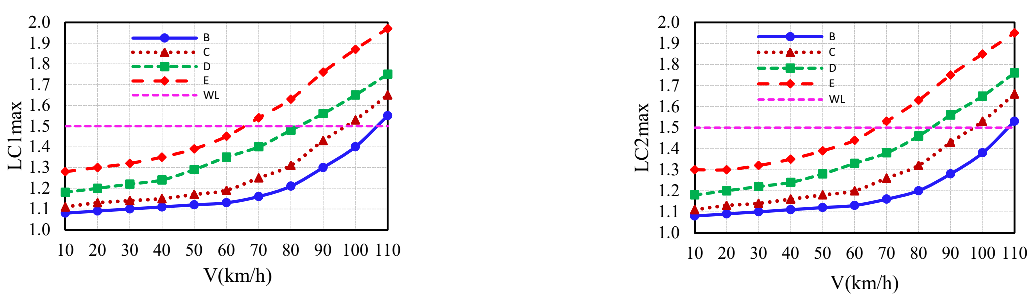
The minimum load coefficient acting on the left and right rear axle (LC_{3min}, LC_{4min}) when the vehicle is running at speeds between 10 and 110 km/h on a random road surface according to ISO 8608:2016 is shown in Figure 3. The WL line is the warning limit (LC_{min}=0.5). As shown in Fig. 3, a bus that is guaranteed to be dynamically safe, the speed must be less than 66 km/h when the vehicle is running on the “class E” road or less than 83 km/h when the vehicle is running on the “class D” road or less than 97 km/h when the vehicle is running on the “class C” road or less than 108 km/h when the vehicle is running on the “class B” road.



(a) (b)

Fig. 3. The minimum load coefficient determined (a) on the left and (b) the right rear axle.

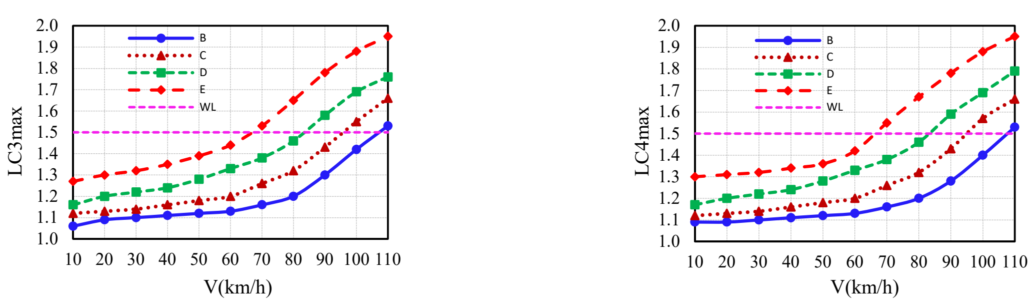
Fig. 4 illustrates the maximum load coefficient acting on the left and right front axle (LC1max, LC2max) when the vehicle is running at speeds between 10 and 110 km/h on a random road surface according to ISO 8608:2016. The WL line is the warning limit (LCmax=1.5). Fig. 4 shows that, when the bus is runing on roads E, D, C, and B according to ISO 8608:2016, the vehicle's speed limit is: 65, 80, 95, 105 km/h, respectively, and the vehicle does not exceed the limit warning and ensures the dynamic safety.



(a) (b)

Fig. 4. The maximum load coefficient determined (a) on the left and (b) the right front axle.

The maximum load coefficient acting on the left and right rear axle (LC3max, LC4max) when the vehicle is running at speeds between 10 and 110 km/h on a random road surface is also presented in Fig. 5. The WL line is the warning limit and equals to LCmax=1.5. As seen from this Figure, a bus that is guaranteed to be dynamically safe, the speed must be less than 67 km/h when the vehicle is running on a “class E” road or less than 84 km/h when the vehicle is running on a “class D” road or less than 96 km/h when the vehicle is running on a “class C” road or less than 106 km/h when the vehicle is running on a “class B” road.



(a) (b)

Fig. 5. The maximum load coefficient determined (a) on the left and (b) the right rear axle.

Variations of the maximum vibration acceleration in longitudinal, lateral, and vertical $(\ddot{x}_{max}, \ddot{y}_{max}, \ddot{z}_{max})$ direction versus the speed of vehicle are shown in Fig. 6 when the Hyundai bus is running at speeds between 10 and 110 km/h on a random road surface. The WL line is the warning limit: $(\ddot{x}_{max} < 1.0 m/s^2, \ddot{y}_{max} < 0.7 m/s^2, \ddot{z}_{max} < 1.5 m/s^2)$. By observing the graph, we can see that, to ensure smooth movement when the bus is running on roads B, C, D, and E according to ISO 8608:2016, the corresponding maximum speed are equal to 65 , 80, 95, 105 km/h, respectively.

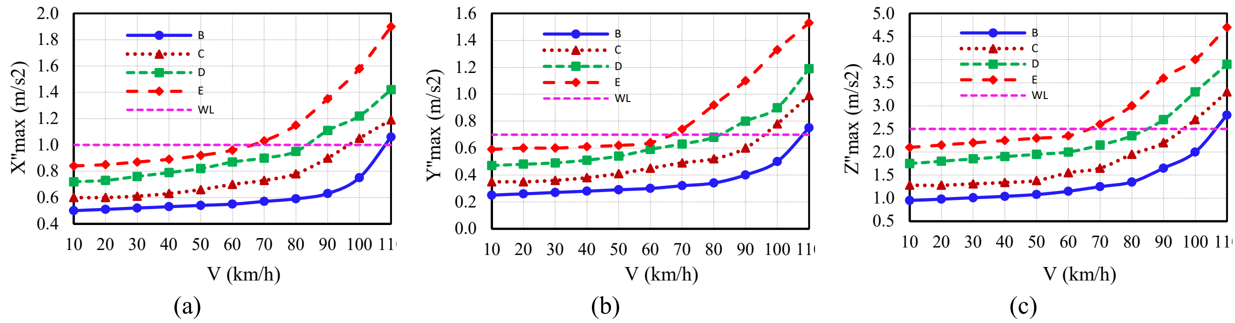


Fig. 6. The maximum vibration acceleration in (a) longitudinal, (b) lateral and (c) vertical directions.

The graphs are used to compare the root mean square of vibration acceleration $RMS(\ddot{Z})$ and the root mean square of wheel load RMS(F_z) of the analyzed Hyundai bus. The variations of root mean square of vibration acceleration using mechanical suspension system and system air suspension system are shown in Fig. 7. A vehicle with an air suspension system has a root mean square of vibration acceleration approximately 26.6% smaller than a vehicle with a mechanical suspension system. The root means square of the wheel load RMS(F_z) of a vehicle with an air suspension system is about 99.6% of that of a vehicle with a mechanical suspension system. The corresponding values of $RMS(\ddot{Z})$ and RMS(F_z) for both air and mechanical suspension systems were increased by increasing the speed of bus as seen from Fig. 7.

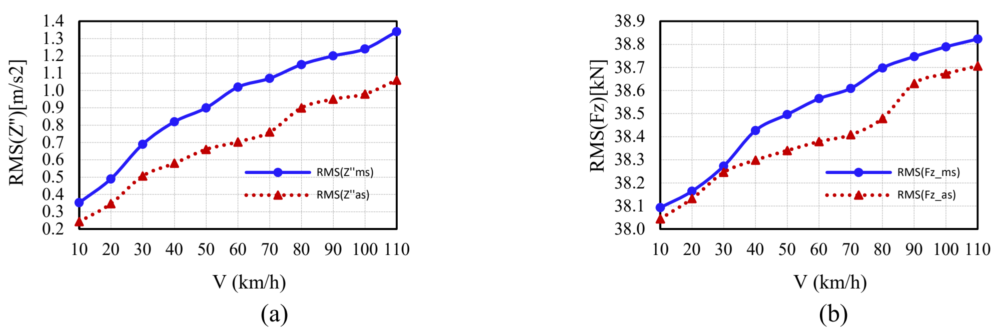


Fig. 7. The variations of (a) $RMS(\ddot{Z})$ and (b) RMS(F_z) versus speed for a vehicle with an air suspension system (red dotted line) and a mechanical suspension system (blue solid line).

4. Conclusions

The Hyundai Universe bus equipped with an air suspension system was dynamically modeled and analyzed to obtain the safe ranges and limits for smooth movement and dynamic safety. When the vehicle passes from the surface of road with different random road surface profiles and roads with "B, C, D and E" classes, the maximum vehicle speed on class B roads is 105km/h, on class C roads is 95km/ h, on class D roads is 80km/h and is 65km/h on class E roads. A vehicle with an air suspension system has a root mean square of vibration acceleration $RMS(\ddot{Z})$ that is approximately 26.6% smaller than a vehicle with a mechanical suspension system. The root means square of the wheel load RMS(F_z) of a vehicle with an air suspension system is about 99.6% of that of a vehicle with a mechanical suspension system.

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